Generator Damper Windings at Wilson Dam

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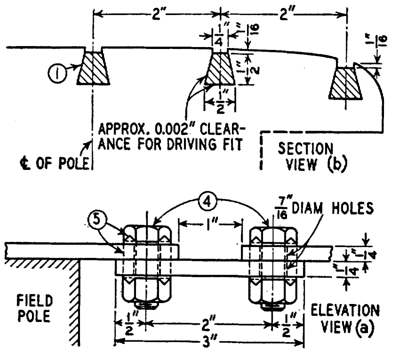
Synopsis: The majority of water-wheel generators now in service have been built without damper windings. Recent technical investigations and laboratory tests have indicated that, in addition to reducing oscillations and improving system stability, damper windings are very effective for reducing high-peak voltages during unbalanced short circuits. This applies particularly under switching conditions of clearing a fault when the load is disconnected from the distant end of a transmission line, and the charging current results in capacitive loading of the unfaulted phases. The existence of similar overvoltage conditions was recognized by the Wilson Dam operating staff and later confirmed by oscillograms during tests. This paper summarizes the studies and tests based on the observed overvoltage conditions and describes a method for adding damper windings to large water-wheel generators which are already installed. Short-circuit tests are extended to generators on a large scale which confirm the earlier theoretical and laboratory tests and demonstrate the advantages to be gained by adding damper windings to other water-wheel generators now in service. The tests show that damper windings in one generator when operated in parallel with another generator without dampers are effective in reducing high-peak voltages during unbalanced faults. Data are given to show the changes in machine reactances due to adding damper windings.

For many years amortisseur, or damper windings, were included in water-wheel generators only when they were required to meet special conditions such as high starting torque for automatic station service, synchronous condenser operation, or system-stability requirements.

The large water-wheel generators at Wilson Dam were installed during 1925 and 1926 without damper windings. The existence of an overvoltage condition during disturbances on an interconnected system was recognized by the Wilson Dam operating staff. At the suggestion of an interconnected company, overfrequency relays were installed for the purpose of disconnecting overspeeding generators although justification of this type of protection was not supported by records obtained from frequency and voltage recorders over a period of several years.



BILL OF MATERIAL		FOR ONE GENERATOR
ITEM	DESCRIPTION	NUMBER REQUIRED
1	1/2" × 1/2" × 1/4" × 50 1/2" LONG COPPER BAR	360
2	1/4" × 1 1/4" × 12 3/8" LONG COPPER BAR CUT TO FIT	144
3	1/4" × 1" × 3" LONG COPPER BAR	144
4	3/8" × 1" HEXAGONAL-HEAD MACHINE BOLT	288
5	1/32" STEEL KEEPER WASHER	288

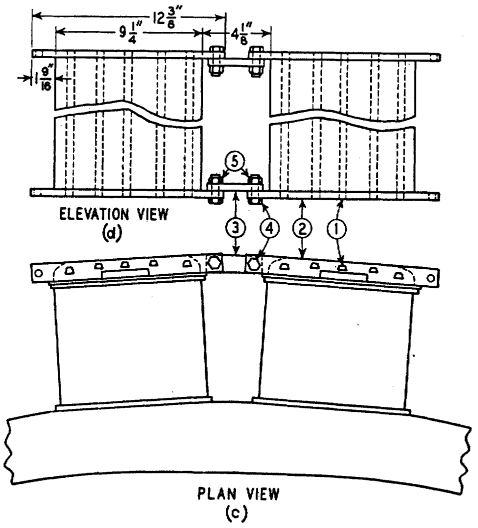


Figure 1. Sketch showing details of damper winding installation

(*a*)—Details of copper connection between adjacent poles

(*b*)—Section view of field pole showing location and dimensions of slots and damper bars

(*c*) and (*d*)—Plan and elevation view assembly sketches

It was expected by local plant engineers that the final explanation of this condition would be obtained during other tests with an oscillograph. During the latter part of 1935 a six-element oscillograph was purchased for use by the electrical testing laboratory. During March 1936, staged tests were made to determine certain relay and equipment characteristics. Other tests followed late in the summer. During the first series of tests one phase of a new lightning arrester broke down. This arrester failure together with the results of preliminary tests led to laboratory studies by the manufacturer and the resulting paper by Wagner.[2] The oscillograms indicated that high-peak voltages were present on the unfaulted phase during line-to-line faults on the distant end of a transmission line which had been taken out of service for tests. Peak voltages as high as 343 kv between high-voltage bus and ground were recorded on the unfaulted phase at the sending end of the 154-kv line. Peak voltages of this magnitude are severe on equipment during the duration of an unbalanced fault.

Technical and Design Features

The generator used for these tests is rated 32,500 kva, 0.8 power factor, 12,000 volts, three-phase, 60 cycles, 100 rpm, vertical axis, and the detailed reactances are given in table III. Staged tests without damper windings were also made on a 25,000-kva generator with other data similar to the above machine except it was built by another manufacturer and similar peak voltages were obtained during these tests.

During conferences and correspondence on the subject, several suggestions were given for the prevention of damage to the equipment due to overvoltage.

1. A set of specially designed spark gaps connected between the high-voltage bus and ground and designed to operate with a few microseconds' delay after the appearance of sustained overvoltage.

2. A combination filter and protective gap connected to the generator leads.

3. The installation of damper windings which would effectively limit the magnitude of unbalanced, distorted phase potentials.

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The authors wish to acknowledge the services of the electrical testing laboratory and operating department personnel who made the tests and their assistance in analyzing the results and also the assistance of the Wilson Dam shops in working out some of the details of the winding installation.

1. For all numbered references, see list at end of paper.

4. Continue the present practice of operating the plant with all generators electrically connected to the same bus, except as required by other system operating conditions. It was also recognized that it was desirable to have other balanced loads particularly synchronous motors or condensers connected to these machines.

The first suggestion was rejected because of operating problems involved together with space requirements and cost. The transformers were already provided with protective gaps. The second suggestion was rejected for substantially the same reasons. Since the effectiveness of the first two suggestions was doubtful for this particular application and would not correct the cause, it was believed that the expense could be used to better advantage in correcting the trouble at its source. The third suggestion for the installation of damper windings was considered the most effective because the machine characteristics directly responsible for the overvoltage condition would be corrected and other benefits of damper windings for improving the stability of rotating machines would be obtained. Both generator manufacturers concurred in recommending the use of damper windings as the best solution for the machines of their own manufacture. Published information on this subject was reviewed and technical investigations were made.

Doherty and Nickle[1] stated that the voltage at short-circuit line to neutral may rise to $(2\,x_q'/x_d') - 1$ times the voltage before short circuit on the open phases. See table III for the identification of x_q' and x_d'. This indicated that for a single-phase-to-neutral fault on the generator it was possible to obtain peak voltages 2.65 times the normal voltage across the terminals of the unfaulted phase.

The manufacturer gave some indications of improvement to be obtained by adding damper windings. These values given below represent the ratio of the peak voltage to normal voltage of the unfaulted phase during a line-to-line fault:

Condition	Generator Only	20 Per Cent External Reactance
Continuous damper		
(*a*) maximum flux	1.34	1.2
(*b*) minimum flux	1.17	1.1
Discontinuous damper		
(*a*) maximum flux	1.84	1.5
(*b*) minimum flux	1.42	1.25

This information indicated the expected reduction in peak voltage to be obtained with each type of damper winding.

The paper by Wagner,[2] written after the designs were completed but before the last short-circuit tests, gave some useful information concerning the effect of inductive, pure resistance, induction-motor and capacity loads on the peak voltages, and the effect of damper windings. On page 1389[2] it is also stated that for a terminal-to-terminal fault on an unloaded machine, the crest of the sum of the odd harmonics measured from the sound phase to the short-circuited phases just after short circuit is equal to $(3/2)(x_q'/x_d')$ times the crest of the normal line-to-neutral voltage for a machine without dampers. For a machine with damper windings the factor is $(3/2)(x_q''/x_d'')$. These reactances can be identified by referring to table III of this paper. If the corresponding values for this generator are used, these formulas would indicate a ratio of 2.54 without dampers and 1.64 with the continuous damper which was added. All of the above-calculated values, unless otherwise indicated, apply to only the generator and are in fair agreement when we consider the state of knowledge of the subject and the differences in assumptions for the equations. Other factors, including the type and location of fault, different external impedances, different transmission-line constants, and the part of the reference-voltage wave at the instant the fault occurs (maximum, minimum, or some intermediate flux condition) should be taken into account, and these result in complicated computations.

During the technical investigations, additional information concerning damper windings and generator characteristics was obtained from published articles by Wagner,[3] Kilgore,[4] Wright,[5] Park and Robertson,[6] Linville,[7] and Wagner and Evans.[8] Clarke, Weygandt, and Concordia[9] have reported some additional information which was not available until our tests were completed.

Preliminary information from the manufacturer suggested the use of five round one-half-inch-diameter copper bars in each pole. This was a good theoretical shape of bar which would result in minimum change in normal field distribution at the surface of the field pole. Round bars are very difficult and expensive to install in the field on account of requiring removal of the laminations from the field pole, possible damage to the field insulation, the cost of making a new die, and requiring a punch press. Round bars can therefore be better installed at the factory.

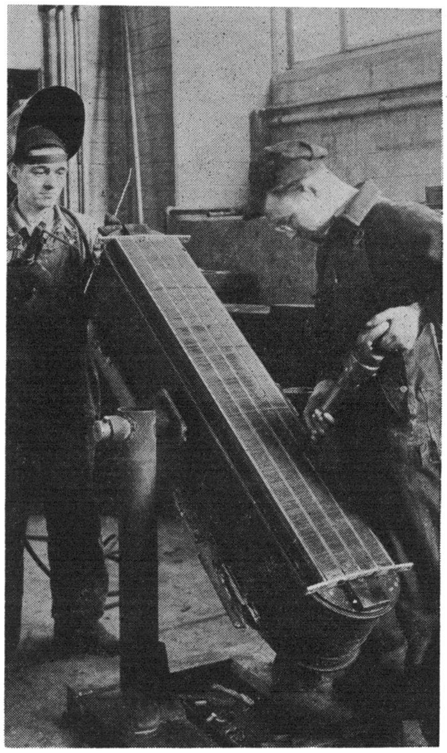

Figure 2. View showing method of swaging copper bars in slots and welding of bars to segments of short-circuiting copper rings

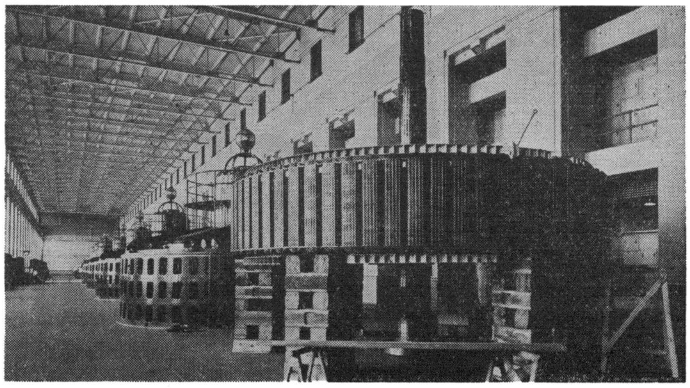

Figure 3. Rotor with field poles and bolted connections between copper segments of adjacent poles nearly completed

During the design, such items as the equipment available in the shops and in the plant, the classes of workmen available to perform each operation, features which would require dismantling the machine, if this is not desired for other maintenance work; obstructions to be avoided; available space; provision for performing each operation, such as machining, welding, etc.; mechanical re-

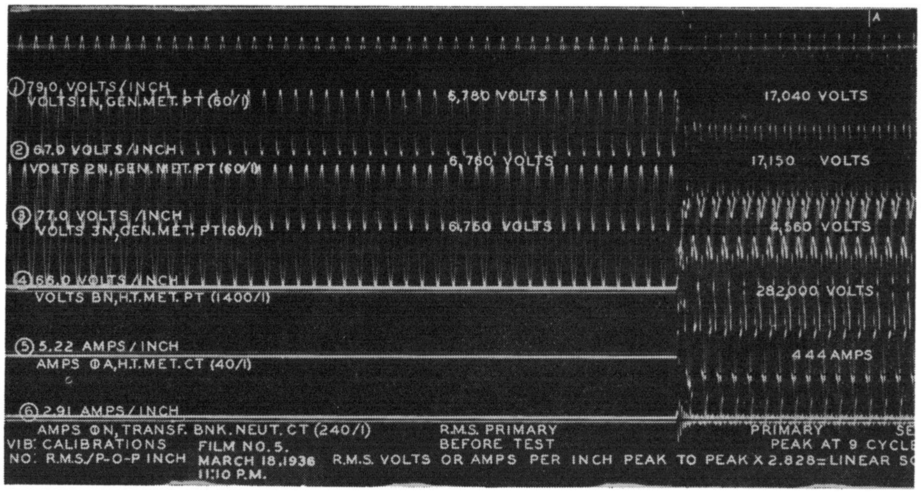

Figure 4. Oscillogram of test number 1

1. Generator phase-*C*-to-neutral voltage
2. Generator phase-*B*-to-neutral voltage
3. Generator phase-*A*-to-neutral voltage
4. Line phase-*B*-to-neutral voltage
5. Line phase-*A* current
6. Transformer neutral current

quirements and factor of safety during maximum overspeed; electrical, insulation, magnetic, and physical requirements, including thermal expansion, etc., had to be considered.

In order to obtain minimum disturbance to the normal magnetic field at the pole face, the one-quarter-inch minimum width of opening into the slot without excessive cost was determined by experiment in the shop. The bars were designed to have approximately the same cross section as a one-half-inch-diameter copper bar. Sketches of the preliminary design for each of the two ratings of main generators in the plant were submitted to the manufacturer of the corresponding machine for comments. The principal changes which resulted were increasing the cross section of copper links between the copper segments of adjacent poles for electrical conductivity and the use of bolted connections instead of using laminated brush copper links welded to the copper bar at each end. Slots at the bolted connection were considered a better provision for thermal expansion and contraction at this location. Sketches of the completed design for this machine are shown in figure 1.

Details of the Damper Winding Installation

This generator had been in service approximately 12 years and the insulation was beginning to show signs of brittleness and other indications of deterioration. Special handling was therefore necessary in order to forestall serious damage to the generator parts during the course of alterations. Each field pole was carefully removed by means of a sling and placed on a truck for transportation from the powerhouse to the shops which was a distance of approximately one-quarter mile. A field pole was first mounted on the bed of a large planer in the conventional manner for cutting the slots, but difficulty was experienced in obtaining uniform slots due to the tendency of the planer tool to "dig in." The scheme selected was a modified milling head attached to the cross-feed of the planer. This equipment was designed and built for this particular application. Each of the five slots were cut in three transverses of the milling head. The angle of the cutter and the position of the planer bed holding the pole-piece was changed for each cut resulting in a slot which has the form of an inverted keystone or dovetail. The field pole was clamped securely, and during the cutting operation it was covered to prevent steel chips from dropping between the windings. The accumulation of chips was blown away by an air jet as required.

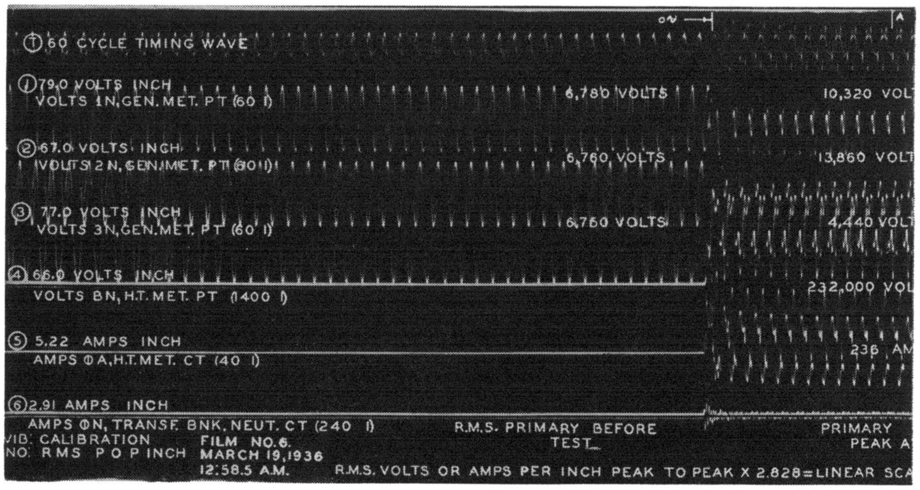

Figure 5. Oscillogram of test number 2

T. 60-cycle timing wave

1. Generator phase-*C*-to-neutral voltage
2. Generator phase-*B*-to-neutral voltage
3. Generator phase-*A*-to-neutral voltage
4. Line phase-*B*-to-neutral voltage
5. Line phase-*A* current
6. Transformer neutral current

The keystone-shaped copper bars were inserted in the slots. Figure 2 shows a cradle structure which was used to support the field poles and also shows how the welding and swaging were done. These operations, of course, were not performed at the same time. The electrical bonding at the ends of the bars was done by means of a carbon arc and "silphos" welding rod. Sufficient clearance was provided between the copper cross-connection and the iron laminations to allow for only differential thermal expansion and contraction. An air hammer was used in swaging the bars to make the outer part of the bars fit more firmly in the slots and prevent noise or excessive vibration while in service.

During the progress of the work, a number of tests were made to check the expansion of the bars while carrying heavy 60-cycle alternating currents. Sample welds and mechanical and electrical tests were made, as required, in order to check the suitability of the installation as well as the electrical and mechanical requirements.

Figure 3 shows the field poles nearly all assembled on the rotor. The copper bars which form the electrical connections between the damper bars of adjacent field poles may also be seen near the upper and lower part of each field pole. These bars are bolted together with steel machine bolts and steel keeper washers are used to prevent them from becoming loose. Each part of the generator was marked before dismantling and the parts were reassembled in their original locations.

The generator rotor and shaft were realigned on being put back together. All parts were cleaned and the coils were treated with insulating varnish during the course of the work. The machine when finally put back in service was in better operating condition than before this work was started.

Short-Circuit Tests

After the generator was reassembled, short-circuit tests were made to determine the effectiveness of the damper windings. The test conditions were made to correspond with those during the tests made before the installation of damper windings.

The generator windings are connected in wye with the neutral point grounded through a resistor. The low-voltage side of the power transformer bank is connected in delta and the high-voltage side is connected in wye with the neutral solidly grounded. Potential transformers connected wye–wye to the low-voltage bus made possible the measurement of phase-to-phase, or phase-to-ground potentials. The potential transformers of the high-voltage metering equipment are normally connected open delta and these were reconnected to measure the potential between the unfaulted phase of the high-voltage bus and ground. High-voltage short-circuit currents were measured by means of wound-type current transformers located either in the high-voltage metering assembly or in the circuit between the transformer-bank neutral point and the station ground.

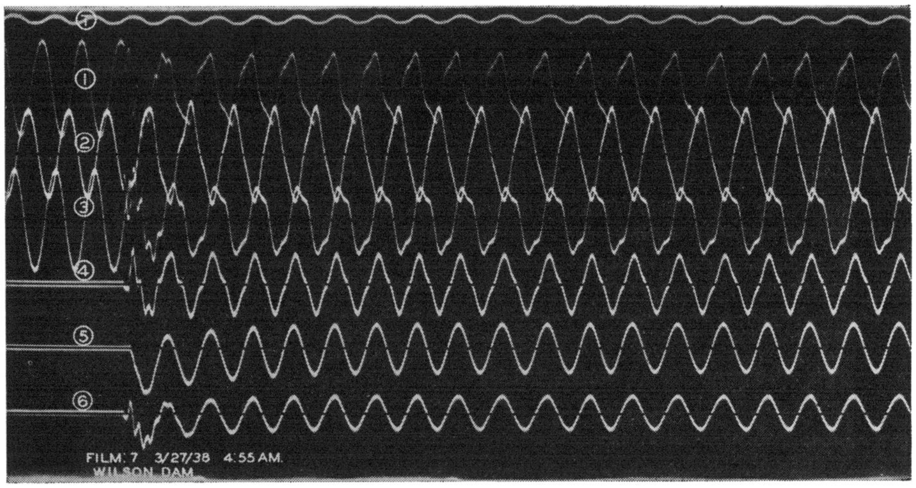

Figure 7. Oscillogram of test number 9

T. 60-cycle timing wave

1. Generator phase-*A*-to-neutral voltage
2. Generator phase-*C*-to-neutral voltage
3. Generator phase-*B*-to-neutral voltage
4. Line phase-*B*-to-neutral voltage
5. Line phase-*A* current
6. Transformer neutral current

Oscillograph records were made of the fault current and the unfaulted phase-to-ground potential on the high-voltage side and the three phase-to-neutral potentials of the generator. Records of field current and other features were taken during some of the tests.

All of these staged short-circuit tests were made on the Wilson Dam to Centerville section of the Wilson-West Nashville 154-kv line. This section of the line was taken out of service and fault connections were made at Centerville, Tenn., which is 68.36 miles from Wilson Dam. The generator combinations were connected to energize the transformer bank at approximately no-load voltage, and the faults were initiated by closing the high-voltage line breaker. Another high-voltage breaker and the low-voltage bus breakers were used for back-up breakers in case of emergency.

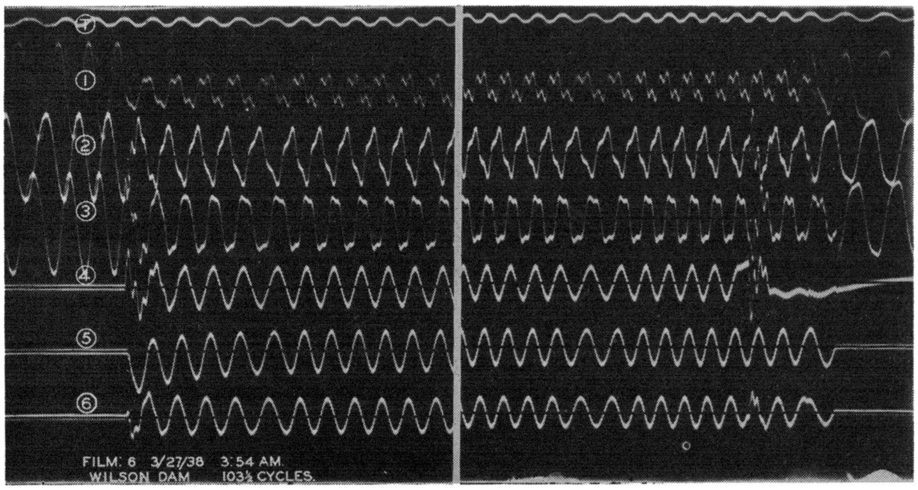

Figure 6. Oscillogram of test number 8

T. 60-cycle timing wave

1. Generator phase-*A*-to-neutral voltage
2. Generator phase-*C*-to-neutral voltage
3. Generator phase-*B*-to-neutral voltage
4. Line phase-*B*-to-neutral voltage
5. Line phase-*A* current
6. Transformer neutral current

Test numbers 1 to 5, inclusive, in table I were made before damper windings were added. Test numbers 6 to 9, inclusive, were made after damper windings were added to generator number 8. During the comparison of results it was observed that tests 1 and 2 were made with 11,500 rms volts between generator terminals; tests 3, 4, and 5 were made at 11,400 volts and tests 6 to 9, inclusive, were made at 10,700 volts. In order to have all tests on the same basis for comparison, the peak voltage between the low-voltage bus and ground before the fault was applied was used as 100 per cent and compared with the corresponding voltages during the fault. The corresponding peak voltage between the high-voltage bus and ground before the fault was applied was obtained by calculation from the transformer ratio and used as 100 per cent for comparison with peak voltages existing during the tests. The transformer ratio was 10,980 volts delta to 154 kv wye. The maximum peak voltage obtained from the oscillogram after the fault was applied was expressed as a percentage of the corresponding initial peak voltage. These percentages were used as the basis for comparison.

These tests were made with no-load voltage on the generators. The fault currents and also the peak voltages during the fault would be higher if the generators had additional excitation with the generators under load. An approximate estimate of the increased voltage peaks due to additional excitation under load could be obtained by using the generator magnetization curve for the corresponding field current under load conditions and using the ratio of the new voltage to the voltages at which these tests were made. An

Table I. Summary of Tests

Test Number	Conditions	Phase	Low-Voltage Bus Phase to Ground Peak Volts		High-Voltage Line Unfaulted Phase to Ground Peak Volts		High-Voltage Line Fault Amperes at Nine Cycles (RMS)*
			(Kv)	(Per Cent)	(Kv)	(Per Cent)	
1	Generators 5 and 6, no reactors, bank 12, phase-*C*-to-*A* fault	*A*	6.54	69.3			444
		B	20.3	215	303	227	
		C	17.84	189			
2	Generator 6 with reactors, bank 12, phase-*C*-to-*A* fault	*A*	5.48	58.3			236
		B	17.25	183	303	227	
		C	14.74	156			
3	Generator 8, regulator in, no reactors, bank 11, phase-*B*-to-*C* fault	*A*	20.55	220.5	343	261	
		B	17.88	192.0			
		C	5.95	63.8			291
4	Generator 8, regulator in, no reactors, bank 11, phase *B*-*C*-ground fault	*A*	13.27	142.2	196.5	150	
		B	12.61	135.3			
		C	5.95	63.8			251
5	Generator 8, regulator in, no reactors, bank 11, phase-*A*-ground fault	*A*	This film				
		B	no				
		C	good		222.2	170	
6	Generator 8, regulator in, bank 11, no reactors, phase-*A*-to-*C* fault	*A*	5.4	61.8			211
		B	11.5	131.8	206.2	166	
		C	13.63	156			
7	Generators 7 and 8, regulators in, no reactors, bank 11, phase-*A*-*C* fault	*A*	5.09	58.3			325
		B	14.0	160.3	231	186	
		C	14.3	164			
8	Generator 8, regulator in, no reactors, bank 11, phase-*A*-*C*-ground fault	*A*	3.08	35.2			245
		B	10.33	118.2	156.7	126.5	
		C	13.1	150			
9	Generator 8, regulator in, no reactors, bank 11, phase-*A*-ground fault	*A*	8.79	100.5			304
		B	9.14	104.7	148.7	119.7	
		C	13.45	154			

* The current waves are not all perfect sine waves. These root-mean-square currents are therefore approximate.

Table II. Comparison of Test Results

Test Conditions	Bus	Peak Volts Without Dampers		Peak Volts Dampers in One Generator		Maximum Per Cent Volts Decrease With Dampers (5)	Maximum Per Cent Volts Increase Without Dampers (6)
		Kv (1)	Per Cent (2)	Kv (3)	Per Cent (4)		
Two generators Phase-phase fault	LV	20.3	215	14.3	164	23.7	31
	HV	303	227	231	186	18.05	22
One generator Phase-phase fault	LV	20.55	220.5	13.63	156	29.2	41.3
	HV	343	261	206.2	166	36.4	57.2
One generator Phase-phase-ground fault	LV	13.27	142.2	13.1	150	5.5*	5.2*
	HV	196.5	150	156.7	126.5	15.65	18.6
One generator Phase-ground fault	LV	Film no good		13.45	154		
	HV	222.2	170	148.7	119.7	29.6	42

Note: Designation (LV) above refers to the maximum bus-to-ground peak voltage of the three phases of the low-voltage bus as recorded in table I, Summary of Tests.

(5)—Column (2) minus column (4), expressed as a percentage of column (2).

(6)—Column (2) minus column (4), expressed as a percentage of column (4).

* An increase in voltage at low-voltage bus is indicated, but the high-voltage line shows a reduction.

exact solution would require detailed calculations involving the internal characteristics of the generator.

Figures 4 to 7, inclusive, are oscillograms of test numbers 1, 2, 8, and 9, respectively. The voltage and current values printed on the films of figures 4 and 5 are the magnitudes at nine cycles made during preliminary analyses. The maximum peak voltages used for the comparison of test results are given in table I.

Table I shows the station combinations used for each test, the type of fault, and the resulting peak voltages and per-cent voltages. Generators 5, 6, 7, and 8 are identical machines and the transformer banks are identical.

Table II is a comparison of test results before and after damper windings were added to generator number 8. This table also shows the per-cent increase in peak volts which were obtained before this type of damper winding was added to the generator. The advantages to be gained by adding damper windings to waterwheel generators now in service are self-evident.

Theoretical calculations were not made to determine if a different length of transmission line would result in higher peak voltages. C. F. Wagner[2] has reported that transmission lines having different lengths or different constants will produce harmonics of different magnitude and therefore different peak voltages during unbalanced faults without damper windings in the generator.

Changes in Generator Reactances

Table III gives the calculated per unit reactances of the generator without damper windings and the corresponding values after damper windings were added. These calculated reactances were obtained from the manufacturer.

Conclusions

1. The results obtained in the reduction of peak voltages for different types of unbalanced faults are summarized in table II. These percentages may change a slight amount if the faults occurred at different points of the voltage wave of the short-circuited phase, but these tests may be considered as representative of the improvements to be expected.

2. These tests show that one generator with damper windings when operated in parallel with another generator without damper windings is very effective for reducing the peak voltages during unbalanced faults.

3. A close inspection of the open-circuit voltage of the oscillograms in figures 6 and 7 will reveal five very small voltage ripples corresponding to the five damper bars in each pole. These voltage ripples, or harmonics, are too feeble to cause telephone interference and they are not noticeable when the machine is operated in parallel with another generator. These harmonics can be reduced by using round copper bars or reducing the width of the dovetail-shaped copper bars near the surface of the field poles, but it would be more expensive and would result in a more difficult mechanical job of machining the slots for the damper bar installation.

4. Since the direct axis subtransient, negative-sequence, and zero-sequence reactances have been reduced, the fault currents are increased by the addition of damper windings. However, for faults beyond the generator bus the external impedance prevents the fault current from being increased in direct proportion to the reduction in generator reactance. Table I shows the comparative root-mean-square fault currents in the high-voltage line nine cycles after the beginning of the fault.

5. It is believed that the installation of damper windings will solve some of the problems of operating companies who have unexplained voltage surges during system disturbances.

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Table III

Per Unit Reactance		Amortisseur		Per Cent Reduction
		Without	With	
Leakage	x	0.22	0.22	0
Direct synchronous	x_d	1.15	1.15	0
Quadrature synchronous	x_q	0.73	0.73	0
Direct transient	x_d'	0.40	0.40	0
Quadrature transient	x_q'	0.73	0.73	0
Direct subtransient	x_d''	0.32	0.265	17.2
Quadrature subtransient	x_q''	0.73	0.29	60.3
Negative sequence	x_2	0.48	0.28	41.7
Zero sequence	x_0	0.14	0.123	12.13

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Discussion

H. E. Bussey (General Electric Company, Atlanta, Ga.): The authors of this paper present in an admirable manner the advantages to be derived by the addition of amortisseur windings to salient-pole generators in the suppression of overvoltages occasioned by short circuits. Great ingenuity is shown in coping with the mechanical problems incident to the installation of amortisseur windings in a generator as large as this, not originally designed for amortisseur windings, and with limited mechanical facilities.

Much has been written on this subject as may be seen from the bibliography accompanying the paper, but only in the last few years has any great weight been given to the importance of amortisseur windings on salient-pole generators in the suppression of high voltages under short-circuit conditions.

The present paper is an important contribution in that it presents the field experience before and after the application of amortisseur windings, so that a direct comparison can be drawn as to the effectiveness of the addition.

The authors mentioned in the bibliography accompanying the paper the work of Clarke, Weygandt, and Concordia as represented by AIEE paper No. 37-74. In this paper some very important considerations are set forth and while the paper by Clarke, Weygandt, and Concordia is now of common knowledge, a statement of the conclusions of this paper may not be out of order in this discussion. It is stated that the principal determining factor for the magnitude of overvoltages caused by line-to-line short circuits is the ratio x_q''/x_d'', of quadrature-axis subtransient reactance to direct-axis subtransient reactance, and that this ratio is a function of the amortisseur characteristic.

The maximum possible overvoltage caused by a line-to-line short circuit on an open-circuited machine is given very closely by the formula

$$e_{max} = 2\frac{x_q''}{x_d''} - 1$$

An important point is that the overvoltage may be considerably increased over the value of this equation by terminal capacitance, the worst condition arising when the capacitive reactance is equal to nine times the negative-sequence reactance of the generator.

In the design of an amortisseur winding for salient-pole generators, consideration must be given not only to the design constants of the generator and to the characteristics of the transmission line and the load, but should also take into account the effect of the design of the amortisseur winding on the reactances of the machine.

For the reasons pointed out, it is desirable that where amortisseur windings are to be applied to existing machines that the manufacturer be freely consulted as much valuable data on the design constants of the generators in question is available from this source. Manufacturers will, I am sure, be glad to co-operate on existing machines not having amortisseur windings.

S. B. Crary (General Electric Company, Schenectady, N. Y.): This paper is of considerable interest as it shows the results of tests made on the same machine under similar conditions before and after an amortisseur winding was installed. Such a direct comparison is not always possible. These tests indicate the improvement that may be realized by the use of an amortisseur winding, and are in general agreement with the mathematical analyses which have recently been made of this phenomena.

Whether or not to install amortisseur windings in water-wheel generators has been the subject of discussion for a number of years. It has been realized that they are generally beneficial. However, these benefits did not always seem to be sufficiently important to justify the additional expense of their installation. As a result, as stated by the authors, there are many water-wheel generators which do not have amortisseur windings. It seems to be in order briefly to review benefits which are now recognized as being obtained by their use in water-wheel generators.

1. Amortisseur windings are of value in providing additional torque for generators which are automatically synchronized when such synchronization may occur when the machine is out of phase or slightly off system speed, and also in increasing the possibility of pulling back into synchronism in case synchronism is lost following a system disturbance. The amortisseur windings give additional torque besides that provided by the main field winding, which may be quite limited except at a slip very close to synchronous speed even when the discharge resistance is in the circuit, because of the inadvisability of using a high value of discharge resistance.

2. Amortisseur windings reduce hunting which may become a definite problem under certain circuit conditions as they provide positive damping when a machine is operating at light load. This is of particular value when it is desired to operate a water-wheel generator as a synchronous condenser or under the condition of overexcitation with small kilowatt load. The tendency for oscillation is increased when the machine is connected by lines having an appreciable amount of resistance to the power system or load.

3. Amortisseur windings, because of their tendency to damp out the oscillations more quickly, are of some benefit in improving the ability of machines to ride through system disturbances, faults, and switching operations. This gain in stability, however, is small. High-resistance amortisseur windings or a double amortisseur winding having low- and high-resistance windings were at one time proposed. The advantage of the high-resistance winding is that it provides a braking torque during the period in which an unbalanced short circuit is on the system. This torque, to the extent that it loads the generator, is of benefit in increasing the stability limits. However, with quick switching and the need for systems to ride through the more severe three-phase faults, the benefits of a high-resistance winding do not seem to justify the expense of its installation.

4. Amortisseur windings are effective in reducing circuit-breaker recovery-voltage rates. Messrs. Park and Skeats have shown that the rate of rise is a function of the ratio x_q''/x_d''.

5. Amortisseur windings are also of benefit in protecting the field winding against current surges in the armature circuit which may be caused by lightning or internal short circuits. The amortisseur winding reduces the induced voltage in the individual field-pole windings and is a factor under these conditions in reducing the field circuit insulation stress.

6. Amortisseur windings are effective in reducing the overvoltages due to unbalanced faults as has been shown recently by two papers, which have analyzed this phenomena, and by the paper under discussion, which has indicated by test the improvement which may be obtained by the use of amortisseur windings.

The reduction of overvoltages due to unbalanced faults is another reason previously not fully recognized why an amortissuer winding should be used in a water-wheel generator. With the effort to co-ordinate insulation levels and provide proper protection for system equipment, the use of a properly designed amortisseur winding is a step in a direction which will allow further economies and improvements to be made. It now appears that with a fuller recognition of these advantages amortisseur windings will be used more in the future than they have been recently.

We believe that it would be very interesting and worth while if the authors could give information as to the ratio of the quadrature to the direct axis reactances before and after installation of the amortisseur windings. If static tests for the x_q'' and x_d'' could be made, this would be an indication of the effectiveness of the amortisseur windings at Wilson Dam, as the ratio of these reactances is a fair measure of the ability of the amortisseur to reduce the overvoltages. In checking over the data given in the paper, apparently the reactance of the transformer banks (11 and 12) used in the tests was not given. This would be of interest if it were desired to make calculations to check the magnitude of overvoltage obtained in the tests.

R. B. George: I wish to acknowledge the fine co-operation we received from the manufacturers during this work, particularly in furnishing generator reactance data and in giving constructive criticism of the proposed design before we started the work of installing the damper windings.

Mr. Bussey's statement concerning how much has been written on this subject is true at the present time, but the most useful contributions for future undertakings were published after our designs were completed. Wagner's paper[2] and Clarke, Weygandt, and Concordia's paper[9] were published after our design was completed. Mr. Wagner also published a series of articles on this subject in the *Electric Journal* during 1938. When my theoretical studies were made, the paper by Doherty and Nickle[1] and Wagner's paper[3] were the only ones I found directly applicable to the problem. Some useful information is contained in references 4 to 8, inclusive, of the bibliography but, since these papers cover different subjects or viewpoints, one should be well acquainted with the technical features of the problem to apply them to this problem.

Mr. Crary's discussion gives a good summary of the uses of damper windings and the benefits to be obtained by installing them.

For the generator without damper windings, the ratio $x_q'/x_d' = 1.825$. After damper windings are added, we use the ratio x_q''/x_d'' which is equal to 1.132. Since the ratio of the quadrature-axis reactance to the corresponding direct-axis reactance is a measure of the peak voltage during unbalanced faults, a reduction of 37.97 per cent is indicated. The calculated values of quadrature-axis and direct-axis reactances are given in table III of the paper. No tests were made to measure the various reactances because such tests are expensive and some of them would require precautions to prevent injury to the windings of a generator which had been in operation for nearly 12 years.

The transformer banks were identical and have 0.221 per cent resistance and 9.88 per cent reactance at 65,000 kva base. The constants of the transmission line are 23.4 ohms resistance, 53 ohms reactance, 349×10^6 mhos total susceptance, length 67 miles, and operating voltage 154 kv.

If studies of combinations of generator, transformer, and lines are made, the inductance corresponding to the negative-sequence reactance should be used at the harmonic frequency being studied. Formulas for various features or combinations may be found in references 1, 2, and 9 of the bibliography.

Reconditioning of Insulating Oils by Activated Alumina

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THE use of insulating oil in electrical equipment carries with it the problem of prevention of deterioration when the oil is subjected to elevated temperatures in the presence of air. Deterioration may be accelerated by the presence of moisture and organic acid. This condition is found in certain types of transformers and oil-filled bushings.

Since oxidation of oil results in an increased acidity which can be determined by tests, it is possible to gauge the rate of deterioration by making tests at intervals. The degree of deterioration is determined by the weight in milligrams of potassium hydroxide required to neutralize the acidity of one gram of oil. This test has been described by the American Society for Testing Materials as a "Tentative Method of Test for Neutralization Number for Petroleum Products and Lubricants," designation: *D*-188-27-*T*. The neutralization number so obtained is the weight in milligrams of potassium hydroxide to neutralize one gram of oil.

Effects of Oxidation

After oil has reached a relatively high acidity number the products of oxidation appear as a sludge in the oil. A pasty coating forms over all parts of the equipment which are immersed in oil. The deposit is greater in thickness where there is a marked differential in temperatures between the oil and the immersed surface. The increase in the thickness of the deposit is especially noticeable on water cooling coils. In the case of transformers, the removal of heat from the core to the heat-radiating surface is retarded and the transformer operates at an increasingly higher temperature under a given load condition. In time the transformer must be removed from service and the sludge washed from the core with a high-pressure stream of oil, and the sludge must be removed from the cooling coils or other radiating surfaces.

In oil-filled bushings a number of factors affect the formation of acid and sludge. Means are usually taken to shield the oil in the gauge glass from sunlight by the use of paint or amber glass. Contact of circulating oil with air should be avoided. Heat from sunlight with a higher ambient temperature on transformer locations indicate that transformer bushing oil should have a higher rate of acid formation. The neutralization number obtained by testing the oil in a large number of 150-kv bushings indicated that sludge formation would start in about four years where the bushings were located on transformers, and in about five years where the bushings were located on oil circuit breakers. After the neutralization number reached 0.5, considerable difficulty was experienced in cleaning the bushings free of sludge. Where the bushings were not equipped with a device to prevent the entrance of moisture, a considerable amount of water was found in the oil. Some bushings are now equipped with a device to prevent the entrance of moisture and at the same time circulation of the oil in the body of the bushing does not bring it in contact with the air surface. The principle of the conservator type of transformer is used in this device.

Control of Oxidation

In recent years the rate of oxidation has been brought under control by the use of two methods in new transformers. One method is the use of the conservator type of transformer, and the other method involves the introduction of nitrogen in the place of air above the surface of the oil.

In several large industrial plants the problem of maintenance of electrical insulating oil in old transformers became acute. About 500,000 kva capacity in both high- and low-voltage transformers were involved in the problem. In 1932 experiments were started with the use of activated alumina both as a desiccating agent and acid adsorption agent in the control of oxidation of oils in steam and

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